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# Analysis of Drying Kinetics and Mathematical Modelling of Peanut Pods using Sunlight, Hot Air, and Microwaves Drying Processes

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ABSTRACT

This study analyzed the drying kinetics of peanut pods employing sun, hot air, and microwave drying techniques, and evaluated their mathematical modeling. The findings demonstrated that sun-drying decreased the moisture content from 26.47% to 8-10% over a duration surpassing 72 hours. Hot air drying at temperatures of 60°C, 80°C, and 100°C, commencing with an initial moisture content of 29.92%, necessitated 810 minutes, 360 minutes, and 660 minutes, respectively. Microwave drying, commencing with an initial moisture content of 23.01%, required 40 minutes, 45 minutes, and 60 minutes at belt velocities of 3 mm/s, 4.9 mm/s, and 6.2 mm/s, respectively, at 300 W. At 400 W, the durations were 24 minutes, 30 minutes, and 40 minutes, respectively. All drying kinetics curves exhibited decreasing rates characteristic of agro-food products. Mathematical modeling analysis identified the Midilli model as the most appropriate, succeeded by the Page, Henderson, and Pabis models, for characterizing moisture loss during the sun, hot air, and belt microwave drying of peanut pods.

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## Introduction

Peanut (Arachis hypogea L.), one of the most widely cultivated and largest oilseed crops globally, has an annual production of approximately 54 million tons. According to FAOSTAT (2022), the leading producing countries are China (17.8 million tons), India (10,134,199 tons), Nigeria (3.4 million tons), the United States of America (2.575 million tons), and Argentina (1.346 million tons). Peanut kernels are a substantial source of oils (44–56%) and proteins (25–35%). Moreover, peanuts are abundant in various health-promoting nutrients, including vitamin A, vitamin B6, and minerals, which may enhance metabolism, bolster memory, improve learning capacity, and retard aging (Xie et al, 2023, Krzyzanowski et al, 2006).

During harvest, peanut pods with a moisture content of 30 to 40 % need drying to prevent spoilage. Handling overly fresh pods, with kernels still attached to the shell, can cause irreversible biological deterioration. Immediate drying reduces moisture to 20-25 %, gradually to 8-10 %. Drying duration varies from days to weeks, affected by weather and drying methods, such as open-air or artificial drying (John and Otten, 1989). Open-air drying exposes products to adverse weather, potentially causing losses from precipitation-induced mold and aflatoxin, compromising quality. Producers mitigate risks using tarps, but improper use leads to poor drying, quality depreciation, and economic losses. Exploring alternative drying methods to ensure safe, rapid drying in any weather is crucial.

Researchers extensively study factors affecting peanut drying, e.g., temperature profiles and moisture reduction under different microwave powers (Boldor et al., 2005; John and Otten, 1989). Comparing traditional practices and solar dryers allowed to evaluate drying kinetics (El-Sayed et al., 2006; Goneli et al., 2017; Hürdoğan et al., 2021). Studies using various methods investigated performance and relate mathematical models to experimental data (Hürdoğan et al., 2021) (Yang et al., 2007).

Conventional drying methods (forced air convection, oven, microwave) need suitable units with specific advantages and disadvantages (Chiewchan et al., 2015). Regardless of method, all dried products lose moisture. Ideal drying faces challenges altering peanuts' qualities and by-products (Babalis et al., 2017), affecting nutritional security, and organoleptic properties.

Although research on hot air and microwave drying emphasizes kinetics and energy consumption, there is a deficiency in the modeling of optimal parameters. The specific objectives are to analyze drying kinetics under various conditions and to model peanut drying using established mathematical frameworks to identify the most appropriate models.

## Materials and Methods

### *Drying Experiments*

In this study, Batem-5025 peanut varieties from the Oilseed Research Institute of Osmaniye Province served as the biological materials. The experiments were performed at the Agricultural Faculty of Çukurova University in Adana, Türkiye. The peanut pods were subjected to multiple drying techniques to attain a moisture content appropriate for extended storage or subsequent processing. Initially, the drying process aimed to attain a safe moisture content of 8-10%, selected for its low water activity (aw 0.67), which is favorable for storage. Three desiccation methods were utilized: solar drying, hot air drying, and microwave drying.

Sun Drying: Sun drying involved exposing samples directly to sunlight on mats or racks placed on the roof terrace at Çukurova University, under Adana/Türkiye's weather conditions. Samples were sheltered at night to prevent moisture absorption. Drying took place over four days, with daytime temperatures around 28°C and nighttime temperatures around 19°C. Humidity remained below 32 %, with constant wind speed of 10 km/h. Moisture loss was monitored by weighing every 12 h.

Peanut samples were dried in the oven at 60°C, 80°C and 100°C in 3 cycles. Two different powers (300 W and 400 W) and three belt speeds (3.7 mm/s, 4.9 mm/s and 6.2 mm/s) were used in the belt microwave drying process. Triplicate samples of approximately 20 g were dried until the required moisture content was reached. The samples were subjected to multiple drying cycles with the exposure time proportional to the number of cycles. The linear velocity was determined by the number of passes and tunnel length.

### *Determination of Moisture Content Profile and Drying Kinetics*

Before initiating any drying process, laboratory procedures were essential to determine the initial moisture content of peanut pods. The FAO method, outlined by Karmas (1980), was employed for this purpose. Approximately 20 g of peanut samples were subjected to 6 hours at 130°C, as outlined by Young et al. (1982), until a stable weight was attained. Mass measurements were conducted utilizing a digital balance (Sartorius GP3202, Göttingen, Germany) with a precision of 0.01 g. Thereafter, the moisture content, represented as a percentage on a wet basis, was computed utilizing Equation 1.

$$\mathrm{MC}(\%) = \frac{\mathrm{M_w}}{\mathrm{M_w}+\mathrm{M_d}} \times 100 \quad (1)$$

Where $M_C$ is the moisture content (%), $M_w$ is the mass of water (g), and $M_d$ is the material's dry mass (g)

Drying kinetics involve continuously weighing samples using an electronic balance to assess mass loss and drying rate of the product. As moisture evaporates during drying, the product's mass diminishes. The reduction in mass attributed to moisture loss was computed using Equation 2. Essentially, establishing the necessary moisture content at a specified time, referred to as the required time, signifies the duration needed to achieve the desired moisture content during drying operations.

$$\Delta \mathrm{W} = \mathrm{W_1} \frac{\mathrm{N_1}-\mathrm{N_2}}{100-\mathrm{N_2}} \text{ with } \Delta \mathrm{W} = \mathrm{W_1} - \mathrm{W_2} \quad (2)$$

Where $\Delta W$ is the mass loss in the product (g); $W_1$ is the initial mass of the sample (g), $W_2$ is the final mass of the sample (g), $N_1$ is the initial moisture content of the sample (%, w.b) and $N_2$ is the final moisture content of the sample (%, w.b).

The drying rate refers to the change in moisture content of the product as measured internally. It is determined by applying the formula outlined in Equation 3:

$$\mathrm{V} = \frac{\mathrm{dM}}{\mathrm{M_S} * \mathrm{dt}} \quad (3)$$

Where V is drying rate or kinetics (g/g.dm), M is the total mass of sample (g), $M_S$ is the mass of dry matter (g), and t is the drying time (s).

### *Mathematical Modelling*

In this study, nine empirical models, each possessing distinct characteristics, are utilized across three different drying methods to establish a characteristic drying law for each process. Several empirical and semi-empirical models have been developed to describe agri-food products' drying kinetics (Midilli and Kucuk, 2003). These models, presented in Table 1, serve to mathematically depict experimental drying curves.

Table 1. Mathematical models provided by various authors for the description of the drying curves

| N° | Models | Equations | References |
|---|---|---|---|
| 1 | Midilli-Kucuk | $Xr = a \exp(-kt^n) + bt$ | Midilli et al. (2002) |
| 2 | Henderson And Pabis | $Xr = a \exp(-kt)$ | Zhang and Litchfield (1991) |
| 3 | Two-Term Exponential | $Xr = a \exp(-kt) + (1-a) \exp(-kat)$ | Sharaf-Eldeen et al. (1980) |
| 4 | Newton | $Xr = \exp(-kt)$ | Ayensu and Asiedu-Bondzie (1986) |
| 5 | Wang And Singh | $Xr = 1+at+bt^2$ | Akpinar et al. (2003) |
| 6 | Page (PG.) | $Xr = \exp(-kt^n)$ | Morey and Li (1984) |
| 7 | Verma (VM.) | $Xr = a \exp(-kt) + (1-a) \exp(-gt)$ | Verma et al. (1985) |
| 8 | Diffusion Approach | $Xr = a \exp(-kt) + (1-a) \exp(-kbt)$ | Yaliz and Ertekin (2001) |
| 9 | Logarithmic (LG.) | $Xr = a \exp(-kt) + c$ | Yağcıoğlu et al. (1999) |

***Statistical Analysis***

The data collected underwent statistical analysis via Sigma Plot software for mathematical modelling. Regression analysis was carried out using the General Nonlinear Modelling procedure to simulate and compare various mathematical drying models with the experimental data on drying kinetics. Procedures such as $R^2$ and standard error estimate were utilized to identify variables with the highest correlation and lowest standard deviation.

## Results

***Moisture Loss Profiles and Drying Kinetics***

*Sun Drying*

Figure 1 show the profiles of moisture loss. It was noted that the fluctuations in moisture content of peanut pods during natural drying closely correlate with environmental weather conditions, despite the slight decrease in moisture content loss curve with an initial moisture content of 26.47 %. When sun-drying peanut pods at varying layer thicknesses of 5 cm, 10 cm, and 15 cm, the average moisture content (w.b) decreased from an initial level of 54.39 % to around 13 % in 52 h, 56 h, and 66 h, respectively (El-Sayed et al., 2006). The findings of the present study underscore that the drying time of peanuts is influenced not only by prevailing weather conditions but also by the thickness of the layers of peanuts destined for drying. The duration of 72 h required to achieve the desired moisture content of 9.04 % confirms this slow dehydration process. Over the course of 72 h, the reduction in humidity was approximately 65.84 %.

Figure 2 shows a gradual decline in the development of the experimental drying kinetics curve. Initially, significant changes in moisture content occur in the early stages of drying and stabilize as drying progresses towards the desired moisture level. According to Can (2000), drying kinetics, including rate variations, are affected by the drying air temperature as evidenced in experiments with pumpkin seeds. In particular, Xie et al, Moukhtar Lati and Bechki (2015) observed that increasing and constant ratesre almost non-existent. Analysis of the decreasing period indicates a slight decrease in the drying rate over time, a phenomenon recorded by Xie et al. (2023) and Akoto et al (2018) on hot air and sun drying of peanuts. These trends can be attributed to the increasing internal resistance to mass transfer, as suggested by Nguyen (2015). According to Nguyen (2015), the drying behavior is related to a tight comparison of the external resistance due to the velocity, temperature and humidity of the air flow and the internal resistance related to the effective diffusivity and size of the product. Moreover, drying curves and speed variations are highly dependent on the moisture content of the product.

*Hot Air Drying*

Different temperatures, namely 100°C, 80°C, and 60°C were applied to hot air dry pre-treated peanut samples. Figure 3 illustrates drying curves showing moisture loss trends in the peanut pod samples. Initially, all samples had a moisture content of 29.92 %. The drying process at each temperature showed a gradual reduction in moisture content over time, followed by stabilization to a constant level. Studies on agro material drying have consistently highlighted the positive impact of air temperature, especially for organic products with high internal water resistance (Belghit et al., 1999a; Mariem and Mabrouk, 2017). However, the time needed to reach the desired moisture content varied significantly with temperature. For example, drying times to achieve 8-10 % moisture content were 6 h at 100°C, 7 h at 80°C, and 13.5 h at 60°C, all shorter than the 14 h reported by Krzyzanowski et al. (2006) for peanuts dried at 34.6°C using pipe technology. These differences can be attributed to initial moisture levels and higher drying temperatures in this study. Munir Ahmad and Mirani (2012) dried peanuts from 23.3 % to 14 % moisture content in 2.4 h using a mobile flat-bed dryer under specific conditions. Increasing temperature decreased drying time for peanut pods, significantly reducing moisture content. Specifically, when temperature rose from 60°C to 100°C, drying time halved. Apart from moisture loss, drying affects other factors, such as the volatility of certain compounds in the dried product. External weather parameters, like ambient air conditions during repeated weighing, may also indirectly influence samples (Belghit et al., 1999a). Generally, higher drying temperatures correlate with lower moisture content, creating a greater deficit in water vapor pressure, which drives outward moisture diffusion (Belkacem, 2016). Higher drying temperatures enhance heat transfer, increasing water molecule energy, facilitating quicker migration within the product, and accelerating their escape.

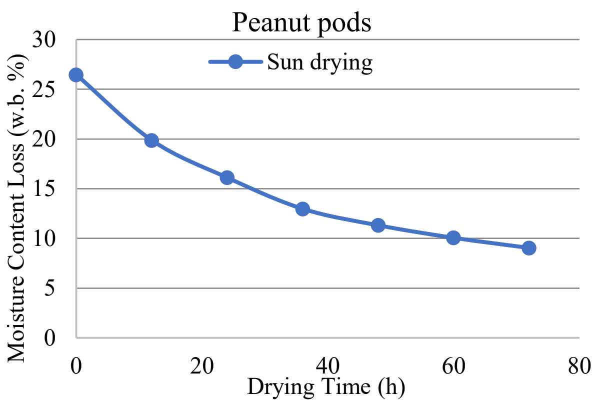


Figure 1. Effect of natural conditions on average moisture loss of sun dried peanuts pods

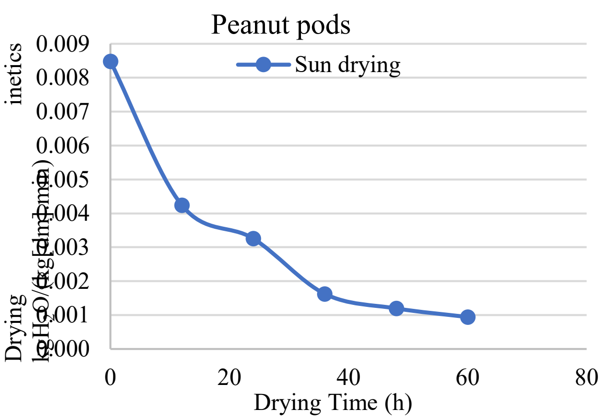


Figure 2. Drying kinetics variations of natural conditions dried peanut pods

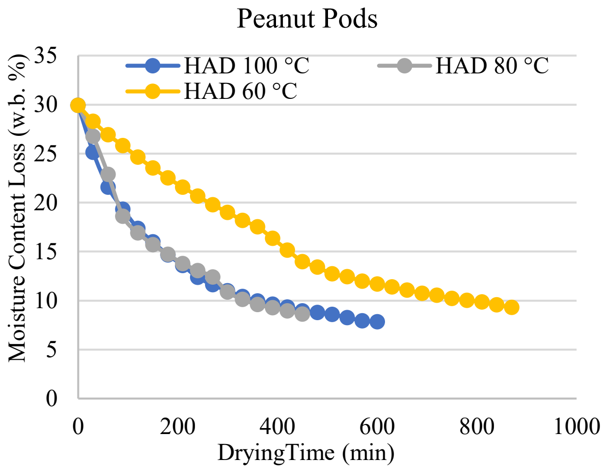


Figure 3. Effect of drying temperatures on the average moisture loss of peanut pods

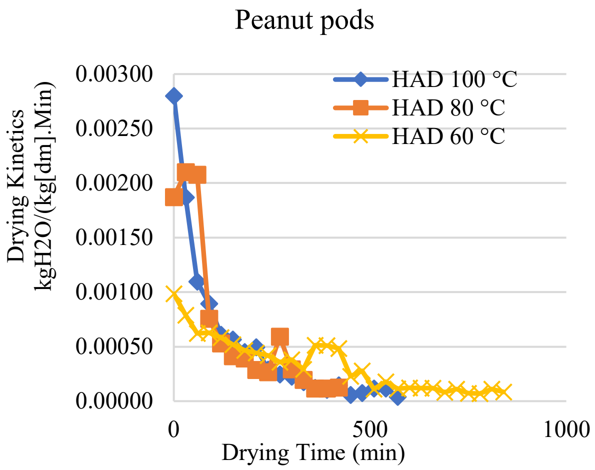


Figure 4. Drying kinetics variations of hot air dried peanut pods

Figure 4 illustrates the progression of drying kinetics over time, highlighting drying temperature as a critical factor. Traditionally, materials such as cellulose, wood, and clay, which are non-hygroscopic and minimally deformable, exhibit three distinct phases: initial product warming, constant speed drying, and decreasing pace period drying (Bonazzi and Bimbenet, 2003). However, analysis of peanut drying curves reveals a deviation from this pattern, characterized by the absence of an initial heating phase and a sustained decline in drying rate. These observations, reflecting agro-food product drying kinetics, are consistent with findings in various studies (Belghit et al., 1999b; Ndukwu, 2009). The phase of decreasing drying rate is likely influenced by structural changes within the dried material and the absence of free water on the product's surface.

The analysis of decreasing periods uncovers two distinct phases in drying kinetics:

Initially, there is a phase characterized by a decreasing drying rate, where the material's physical properties progressively impact the kinetics. This decrease in drying rate is often attributed to the increasing internal resistance to mass transfer, as indicated by Nguyen (2015). Increasing the drying temperature generally boosts the drying rate, particularly at the start of drying, prominently seen in the data at 100°C and 80°C. However, towards the end of the operation, the influence of temperature diminishes as nearly all free and bound water molecules have evaporated, leaving only those bound to the product's structure unaffected by the drying process (Mariem and Mabrouk, 2017). Temperature is identified as the most influential factor affecting drying kinetics.

The second phase occurs as the material enters the hygroscopic domain entirely. Here, the drying kinetics gradually diminishes until it aligns with the material's equilibrium with the external conditions.

### *Belt Microwave Drying*

In the section of Belt Microwave Drying, the effects of two power intensities (300 W and 400 W) and three belt velocities of microwave dryers were examined. Figure 5 illustrates the moisture content loss profiles. Initially, all samples had a consistent moisture content of 23.01 %. Results indicated a gradual decrease in moisture content with increasing power intensities. Towards the end of drying, where the rate stabilizes, the water potential at the surface remains insignificant compared to that of the microwaves, resulting in a slight variation in the water potential differential.

Delwiche et al. (1986) similarly observed this progressive decrease in moisture content in peanut pods and kernels with varying power levels. With a power intensity of 300 W, exposure times to achieve the desired moisture content were 40 min, 45 min, and 60 min, corresponding to velocities of 6.2 mm/s (250 rpm), 4.9 mm/s (200 rpm), and 3.7 mm/s (150 rpm). Using 400 W, exposure times were 24 min, 30 min, and 40 min, with corresponding velocities. These findings suggest that increasing power intensity or belt velocity gradually reduces the required drying time.

In essence, higher power leads to increased microwave energy (Boldor et al., 2005), while lower belt velocity extends exposure time in the dryer, consequently affecting the temperature and moisture of peanuts. These observations align with the findings of Schirack et al. (2007), who studied a continuous belt microwave system for blanching peanuts and noted that higher power and temperature levels could rapidly reduce moisture content.

Figure 6 illustrates the variation in drying kinetics. Analysis of the drying kinetics curves indicates a single phase characterized by a decreasing drying rate, without an initial phase of increasing and constant heating rate. These findings are consistent with experiments conducted by (Lamyae L. et al., 2015). Examining the warming phase emphasizes the significant influence of microwave power intensity and belt velocity on drying kinetics. Higher power levels and lower belt velocities initially accelerate the drying rate. However, as drying progresses within the tunnel, the rate gradually diminishes until it reaches equilibrium with external conditions. These trends are influenced by the inherent properties of peanuts and the conduction properties of the boundary layer, which maintain relative constancy during this phase. As the product's surface continues to dry, changes in these properties impede mass transfer, leading to a reduction in moisture content.

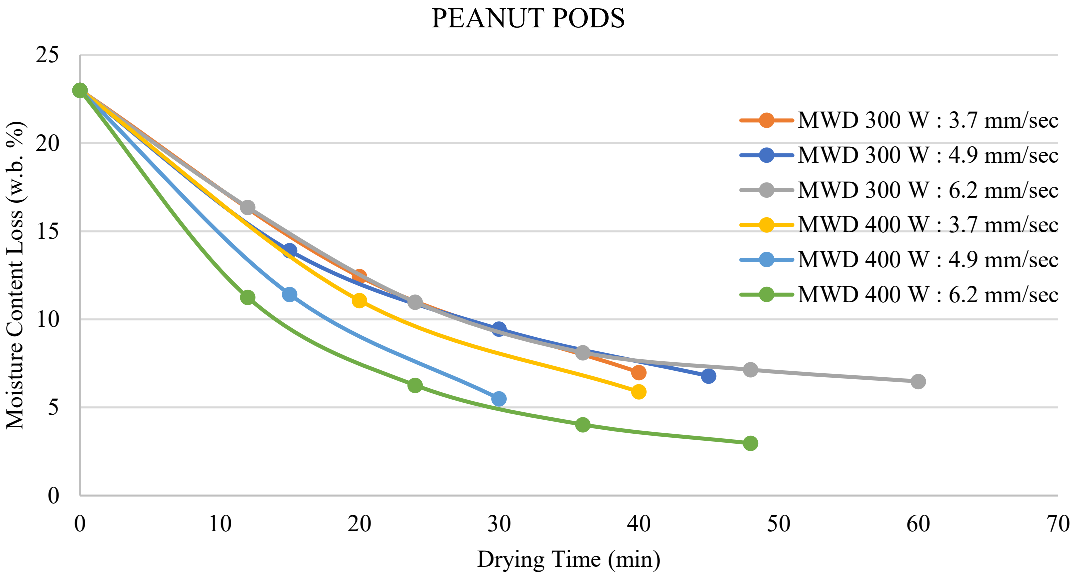


Figure 5. Effect of power intensities and belt velocities on average moisture loss in belt microwave dried peanuts pods

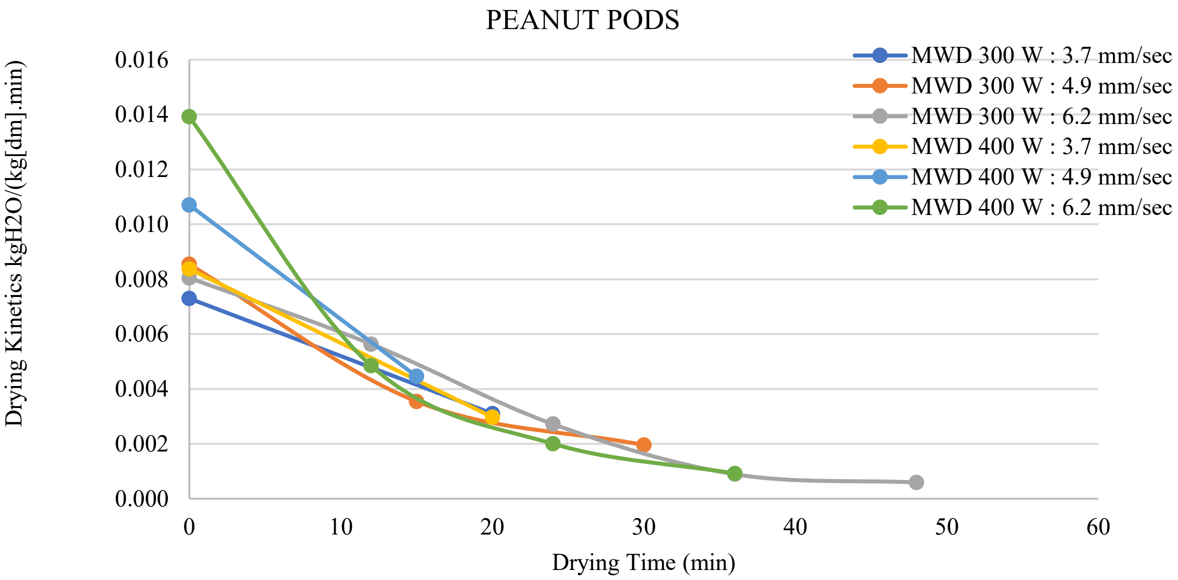


Figure 6. Drying kinetics variations of belt microwave dried peanut pods

***Mathematical Modelling of Drying Peanuts***

The drying kinetics data from drying methods were analysed using mathematical models, with semi-empirical equations representing the moisture content variation over time during drying. To ensure agreement with experimental data, these equations include adjusted constants determined through nonlinear regression. The efficiency of each model was assessed through statistical parameters such as a high correlation coefficient ($R^2$) approaching 1 and a minimum standard deviation ($\chi$) approaching 0.

***Modelling of Sun Drying***

Table 2 illustrates that in terms of sun drying, the Midilli-Kucuk and Page models demonstrate superior coefficients for describing peanut pod drying under natural meteorological conditions. Correlation coefficients ($R^2$) range from 0.1864 to 0.8600, with standard deviations between 0.0015 and 0.0028. Hürdoğan et al. (2021) identified the random tree and Quintic models as best suited for estimating moisture content and drying rate of solar-dried peanuts. Conversely, Midilli and Kucuk (2003) found the Two-Term Exponential model effective for thin-layer sun drying of pistachios. The Page model accurately described moisture content evolution during thin-layer solar drying of raw rice seeds (Basunia and Abe, 2001). For vegetables, Yaliz and Ertekin (2001) reported the diffusion approximation model as optimal for pumpkin and green pepper, the Two-Term Exponential model for stuffed pepper and onion, and the Page model for green beans. Furthermore, the Exponential model was found to better represent the characteristics of thin-layer sun drying of mulberry fruits compared to Page's model.

Table 3. Modelling of moisture content according to drying time for peanut pods in the sun drying

| N° | Models | $R^2$ | χ |
|---|---|---|---|
| 1 | Midilli-Kucuk | 0.8600 | 0.0015 |
| 2 | Henderson And Pabis | 0.1070 | 0.0030 |
| 3 | Two-Term Exponential | NAN | 0.4472 |
| 4 | Newton | NAN | 0.4083 |
| 5 | Wang And Singh | NAN | 0.5109 |
| 6 | Page | 0.1864 | 0.0028 |
| 7 | Verma | NAN | 0.5000 |
| 8 | Diffusion Approach | NAN | 0.5000 |
| 9 | Logarithmic | 0.2050 | 0.0031 |

Bests mathematical models; 1st. Midilli-Kucuk model's; 2nd. Page model's

Table 4. Modelling of moisture content according to drying time for peanut pods in the hot air drying

| N° | Models | 60 °C | | 80 °C | | 100 °C | |
|---|---|---|---|---|---|---|---|
| | | $R^2$ | χ | $R^2$ | χ | $R^2$ | χ |
| 1 | Midilli-Kucuk | 0.9065 | 0.0001 | 0.9023 | 0.0003 | 0.9930 | 0.0001 |
| 2 | Henderson And Pabis | 0.8799 | 0.0001 | 0.8371 | 0.0003 | 0.9694 | 0.0001 |
| 3 | Two-Term Exponential | NAN | 0.0004 | NAN | 0.0009 | 0.2532 | 0.0006 |
| 4 | Newton | NAN | 0.0004 | NAN | 0.0009 | 0.2532 | 0.0006 |
| 5 | Wang And Singh | NAN | 0.3216 | NAN | 0.3106 | NAN | 0.3161 |
| 6 | Page | 0.8030 | 0.0001 | 0.7217 | 0.0004 | 0.9812 | 0.0001 |
| 7 | Verma | 0.8948 | 0.0000 | 0.8371 | 0.0003 | 0.9818 | 0.0001 |
| 8 | Diffusion Approach | 0.8948 | 0.0001 | 0.8371 | 0.0003 | 0.9818 | 0.0001 |
| 9 | Logarithmic | 0.8811 | 0.0001 | 0.8380 | 0.0003 | 0.9860 | 0.0001 |

Bests mathematical models; 1st. Midilli-Kucuk's model; 2nd. Logarithmic's mod

Table 5. Modelling of moisture content according to drying time for peanut pods in belt microwave drying at 300 W

| N° | Models | 300 W | | | | | |
|---|---|---|---|---|---|---|---|
| | | 3.7 mm/s (150 rpm) | | 4.9 mm/s (200 rpm) | | 6.2 mm/s (250 rpm) | |
| | | $R^2$ | χ | $R^2$ | χ | $R^2$ | χ |
| 1 | Midilli-Kucuk | 1.000 | (+inf) | 1.000 | (+inf) | 0.9999 | 0.0005 |
| 2 | Henderson And Pabis | 0.1150 | 0.0975 | 0.0006 | 0.0671 | 0.0283 | 0.0425 |
| 3 | Two-Term Exponential | NAN | 1.0004 | NAN | 0.7076 | NAN | 0.5002 |
| 4 | Newton | NAN | 0.7076 | NAN | 0.5779 | NAN | 0.4476 |
| 5 | Wang And Singh | NAN | 1.000 | NAN | 0.7174 | NAN | 0.5100 |
| 6 | Page | 0.6720 | 0.0593 | 0.4106 | 0.0515 | 0.2062 | 0.0385 |
| 7 | Verma | NAN | (+inf) | NAN | 1.0000 | NAN | 0.5770 |
| 8 | Diffusion Approach | NAN | (+inf) | NAN | 1.0000 | NAN | 0.5770 |
| 9 | Logarithmic | 0.6720 | (+inf) | 0.4110 | 0.0729 | 0.2350 | 0.0436 |

Bests mathematical models: 1st. Page's model; 2nd. Midilli-Kucuk's model

Table 6. Modelling of moisture content according to drying time for peanut pods in belt :microwave drying at 400 W

| N° | Models | 400 W | | | | | |
|---|---|---|---|---|---|---|---|
| | | 3.7 mm/s (150 rpm) | | 4.9 mm/s (200 rpm) | | 6.2 mm/s (250 rpm) | |
| | | $R^2$ | χ | $R^2$ | χ | $R^2$ | χ |
| 1 | Midilli-Kucuk | 1.0000 | (+inf) | 1.000 | (+inf) | 1.0000 | 0.0000 |
| 2 | Henderson And Pabis | 0.0173 | 0.1560 | 0.1100 | 0.1080 | 0.0000 | 0.0400 |
| 3 | Two-Term Exponential | NAN | 1.0000 | -75.907 | 1.0004 | -207.18 | 0.5776 |
| 4 | Newton | NAN | 0.7071 | -75.967 | 0.7076 | -207.28 | 0.5003 |
| 5 | Wang And Singh | NAN | 1.0000 | -75.850 | 1.0000 | -211.42 | 0.5834 |
| 6 | Page | 0.4143 | 0.1200 | 0.6626 | 0.0663 | 0.3252 | 0.0329 |
| 7 | Verma | NAN | (+inf) | -75.850 | (+inf) | -207.05 | 0.7070 |
| 8 | Diffusion Approach | NAN | (+inf) | -75.850 | (+inf) | -207.05 | 0.7070 |
| 9 | Logarithmic | 0.4140 | (+inf) | 0.6630 | (+inf) | 0.3250 | 0.0403 |

Bests mathematical models: 1st. Page's model; 2nd. Midilli-Kucuk's model

***Modelling of Hot Air Drying***

Table 3 presents the main findings from the statistical analysis of the mathematical modelling of peanut pod drying. The Midilli-Kucuk model accurately predicts the drying process of dried peanut pods at 60°C, 80°C, and 100°C, with a correlation coefficient ($R^2$) ranging from 0.9023 to 0.9930 and a standard deviation ranging from 0.0001 to 0.0003. Additionally, the Logarithm model effectively characterizes the drying process of peanut pods at 80°C and 100°C, while the Verma model yields favourable coefficients particularly for drying at 60°C. nut pods in hot air drying.

In this study, observations confirmed by Yang et al. (2007) indicated that the Henderson-Pabis model is the most suitable for describing the drying of thin peanut layers. Conversely, Tayel et al. (2015) found that the Lewis model effectively describes the drying behaviour of peanut pods under high humidity conditions. Xie et al. (2022) demonstrated that the logarithmic model is appropriate for peanut pod drying under hot air at 40°C with an air speed of 0.5 m/s. Goneli et al. (2017) concluded that the Two-Term, Midilli-Kucuk, Page, and Thompson Diffusion Approximation models are suitable for representing peanut kernel drying kinetics during forced air drying. Fokone et al. (2013) found that the exponential model is a perfect fit for describing carrot drying behaviour across different temperatures, air velocities, and relative humidity. Akpinar et al. (2003) indicated that an approximation of the diffusion model satisfactorily describes the drying curve of red peppers under specific drying conditions.

### *Belt Microwave Drying*

The findings in Tables 4 and 5 regarding microwave drying demonstrate that, the Page and Midilli-Kucuk model adequately describe the drying of peanut pods. For power intensities of 300 W and 400 W applied to three belt velocities, correlation coefficients ($R^2$) range from 0.2062 to 1.0000, with standard deviations ranging from 0.0000 to 0.1202. These results are consistent with Beyza (2018) research on microwave drying of pomegranate grains. However, John and Otten (1989) found that the Two-Term Exponential model accurately predicts the microwave drying of peanut pods and kernels.

## Conclusion

This study examined the independent effects of sun drying, hot air drying, and belt microwave drying on the moisture content of peanuts, using numerical models to assess their consistency. Peanut pods were initially sun dried for 72 h to reach optimal moisture levels. Subsequently, hot air drying at 80°C reduced the drying time to 7 h, while microwave belt drying at 400 W and 6.2 mm/s (250 rpm) further reduced it to 24 min. Microwave drying is economically feasible with sun drying whereas hot air drying of peanuts pods needs more energy to achieve the safe moisture content.

Results indicate that drying kinetics followed typical patterns observed in agricultural products across all methods and variables. Theoretical models such as "Midilli-Kucuk" and "Henderson and Pabis" accurately represented moisture content variations in hot air drying. Conversely, Page's and Midilli's models effectively described moisture content variations during continuous belt microwave and sun drying. Among the nine models examined, the "Wang Sangh" model was found to be the least suitable for all drying conditions.

## Declarations

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*Data availability statement:* The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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